—研究論文—
*Scientific Papers*

# Aerophotographic Interpretation of Surface Features and an Estimation of Ice Discharge at the Outlet of the Shirase Drainage Basin, Antarctica

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# 南極氷床，白瀬流域沿岸における表面形態の空中写真判読と氷の流出量の推定

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**要旨**: 1962 年，1969 年，1975 年および 1977 年に撮影された空中写真の解析をもとに，白瀬氷河氷舌部の特徴的な表面構造と，斜面下降風系について述べ，また白瀬流域からの流出量を，氷舌部での流動量と氷厚が異なる 3 つの副流域に分け，算定した．氷の流動速度は，氷山の移動量から求め，白瀬氷河氷舌部については，平均で 2500 $m \cdot a^{-1}$，白瀬氷河西側の sheet flow については，360 $m \cdot a^{-1}$ の値を得た．Calving front 付近での氷山の厚さは，2 級図化機を用いての空中写真測量による氷山高から求めた．これらの値から，白瀬流域からの氷の流出量として，13.4 ～14.7×$10^9$ $t \cdot a^{-1}$ を得た．また，白瀬流域の過去数年間の質量収支として，これまでに報告された流入量との差から，−0.7～−2.0×$10^9$ $t \cdot a^{-1}$ を得た．

***Abstract***: Aerophotographs taken by the Japanese Antarctic Research Expedition in 1962, 1969, 1975 and 1977 are analyzed to classify distinctive surface structures, katabatic wind regime at the terminus of the Shirase Glacier (70°S, 39°E), and ice discharge from the Shirase drainage basin is calculated as the sum of ice discharge from three subdivisional drainages with different flow velocities and ice thickness at their outlets. From the displacement of icebergs, the flow velocities of about 2500 $m \cdot a^{-1}$ and about 360 $m \cdot a^{-1}$ are obtained for the Shirase Glacier and the sheet flow in the west of the Shirase Glacier, respectively. Thicknesses of the icebergs near calving front are also obtained by the aerophotogrammetry. The total discharge from the Shirase drainage basin, 13.4 to 14.7×$10^9$ $t \cdot a^{-1}$, is reported to be more accurate than the values by other authors. Substracting the total discharge from the income previously reported by the other authors, the mass budget of the ice sheet in the basin is estimated to be −0.7 to −2.0×$10^9$ $t \cdot a^{-1}$ during the last several years.

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## 1. Introduction

Since 1957, the Japanese Antarctic Research Expedition has taken a number of aerophotographs along the coast near Syowa Station (69°00′S, 39°35′E) to compile topographic maps between 30°E and 45°E (GEOGRAPHICAL SURVEY INSTITUTE, 1981), and these aerophotographs have been used to study the surface features of glaciers and to estimate the ice discharges at the outlets of drainages.

The Shirase drainage basin delimitated by SHIMIZU *et al.* (1978a) is the largest basin with an area of $2\times10^5$ km$^2$, the mean thickness of 1840 m and the total volume of $3.7\times10^5$ km$^3$ in Mizuho Plateau, where the Shirase Glacier is the main outlet (Fig. 1). The Shirase Glacier is the largest stream flow along the coast of Lützow-Holm Bay. In the image of ERTS taken in January 1974, the width and the length of floating tongue of the Shirase Glacier were about 11 km and 60 km respectively.

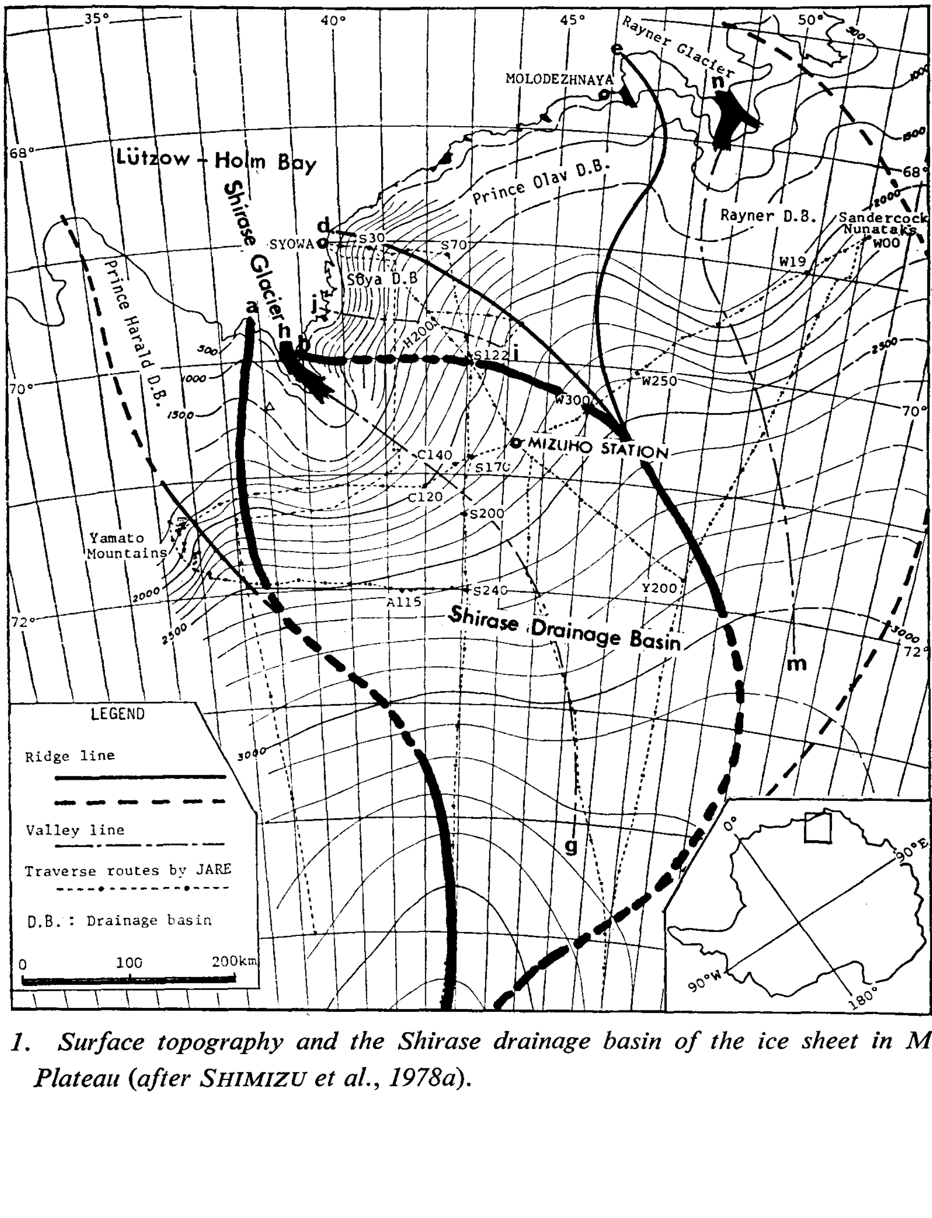

*Fig. 1. Surface topography and the Shirase drainage basin of the ice sheet in Mizuho Plateau (after SHIMIZU et al., 1978a).*

The estimation of discharge from the Shirase Glacier is, therefore, most important to study the mass budget of the Shirase drainage basin. In analyzing aerophotographs, NAKAWO *et al.* (1978) gave a discharge value of $7.4 \pm 1.9 \times 10^9$ t·a$^{-1}$. But their method was inaccurate in estimating the ice thickness and calculating the total discharge. SHIMIZU *et al.* (1978b) estimated the mass budget of the Shirase drainage basin to be 0.7 to $2.0 \times 10^9$ t·a$^{-1}$ using the ice discharge value of NAKAWO *et al.* (1978) who disregarded the sheet flow discharge from the 20 km long coast between 69°45′S and 70°S to the west of the Shirase Glacier.

In this paper, surface morphological feature of the Shirase Glacier deciphered from aerophotographs is presented. The outlet of the Shirase drainage basin is divided into three subdivisional parts with different flow velocities and ice thickness. The re-estimation of ice discharge from the Shirase drainage basin is made in each subdivisional outlet using the mean annual velocity of ice flow and ice thickness in analyzing aerophotographs taken in 1962, 1969, 1975 and 1977.

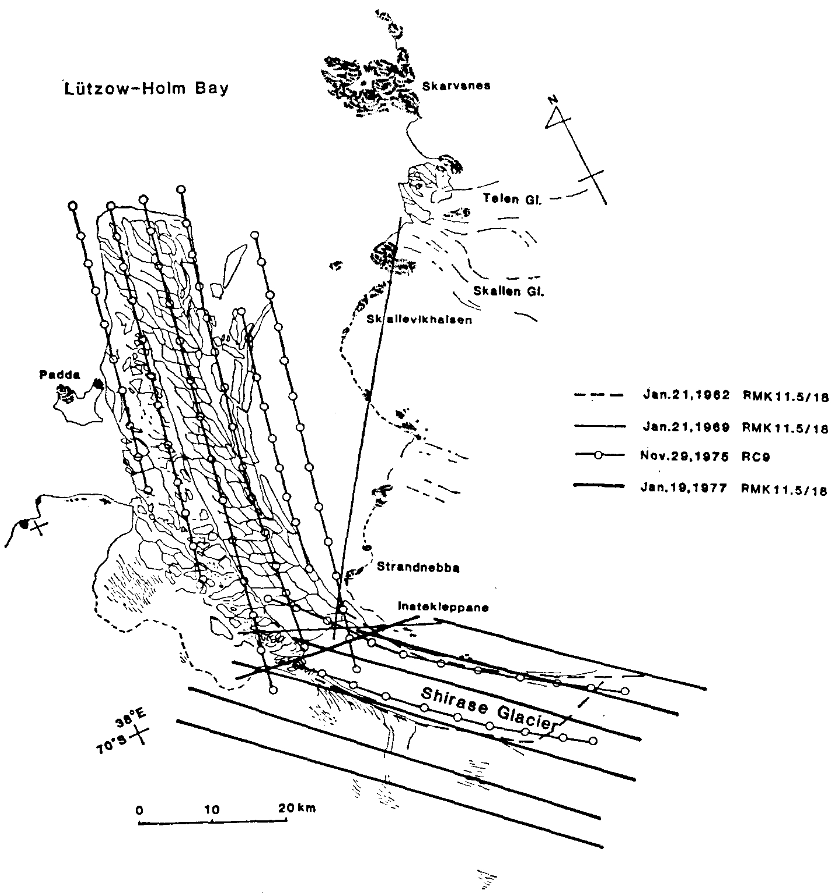


*Fig. 2. Courses of aerophotography over the terminus area of the Shirase Glacier in 1962, 1969, 1975 and 1977.*

Aerophotographing courses over the outlet of the Shirase drainage basin are shown in Fig. 2. On four occasions of January 21, 1962, January 21, 1969, November 29, 1975 and January 19, 1977, aerophotographs of the terminus of the Shirase Glacier were taken with Carl Zeiss RMK 11.5/18 and Wild RC9. The flight altitude, airphoto scale, and the number of aerophtographs are listed in Table 1.

*Table 1. Records of aerophotography over the terminus area of the Shirase Glacier in 1962, 1969, 1975 and 1977.*

| Date | Altitude (m) | Aircraft | Surveying camera | Scale | Number of photos |
|---|---|---|---|---|---|
| Jan. 21, 1962 | 3000 | Cessna 185 | RMK11.5/18 | 1:26000 | 48 |
| Jan. 21, 1969 | 3000 | LASA 60 | RMK11.5/18 | 1:26000 | 23 |
| Nov. 29, 1975 | 3000 | Cessna A185F | RC9 | 1:34000 | 154 |
| Jan. 19, 1977 | 3000 | Cessna A185F | RMK11.5/18 | 1:26000 | 241 |

## 2. Surface Feature of the Shirase Glacier

From the mosaics of contact prints of the aerophotographs, the surface structures such as crevasses, cracks, depression, ice ridges and ice troughs, ablation ponds, bare ice, icebergs, exposed rocks and others were deciphered and the prevailing wind directions in many places were deduced from the direction of drifted snow. Interpreted surface features are classified as shown by the legend given in Fig. 3.

### 2.1. Surface feature in January 1962

Surface feature of the Shirase Glacier observed on January 21, 1962 is shown in Fig. 4a. In the flight of January 21, 1962, aerophotographs along the west and the east lateral of the glacier are not overlapped and immovable land marks are not photographed on the west side. With the aid of aerophotographs taken at later dates, two mosaics were fixed in referring to the position of the junction of a tributary glacier flowing from the west to the Shirase Glacier.

On both sides of the main stream of the Shirase Glacier, longitudinal ice ridges and troughs are observed. A transverse crack occurs from near the exposed rock Instekleppane and calving of icebergs begins to occur in the downstream of Instekleppane.

On the east side, a longitudinal ice trough starts from a lake 2700 m long and 360 m wide in a depression of 150 m from the surrounding ice. The height of the lake surface was measured from stereo-pairs of photographs where Oku-hyôga Rock (155 m above sea level in the map "Lützow-Holm Bay" (1963) compiled by Geographical Survey Institute, Japan) is photographed. Taking parallax bar readings for three stereo-pairs, the relative height of $-144\pm15$ m was obtained with reference to the height of Oku-hyôga Rock. As the height control points are not located in the vicinity of the Shirase Glacier, the height of Oku-hyôga Rock seems to have been estimated with an accuracy of $\pm 10$ m relative to the flat sea ice surface. Therefore, there is a possibility that the level of the lake coincides with the sea level, that is, the lake is connected to the sea. The relative height $h$ and the standard error $\mu_{dh}$ are calculated by the following equations:

$$h = H \cdot P/B$$

$$\mu_{dh} = \pm\{(P/BdH)^2 + (H \cdot P/B^2dB)^2 + (H/BdP)^2\}^{1/2}$$

where $H$, $P$ and $B$ are flight altitude, parallax difference and the distance between two principal points respectively, and $dH$, $dP$ and $dB$ are errors of $H$, $P$ and $B$ respectively.

Two prevailing wind systems are deduced from directions of drifted snow; one is along the main valley of the glacier, being more distinctive on the west side, and the other is along the continental slope in the east of the Shirase Glacier. These wind systems seem to be katabatic winds blowing down the slope. Bare ice area exists on the continental slope where the movement of ice is relatively small, but not on ice stream.

### 2.2. Surface feature in January 1969

Two aerophoto flights were taken on January 21, 1969; one from Instekleppane, crossing the Shirase Glacier, to the west where three unnamed exposed rocks are existing, and the other from Strandnebba to the center of the glacier. The aerophotographed area shown in Fig. 4b covers a part of the floating tongue of the Shirase Glacier.

Fig. 4b indicates the development of deep cracks reaching the sea and icebergs calved from the glacier. Two crossing wind systems on the floating tongue are deduced from the directions of drifted snow. These wind systems seem to be of katabatic origin, one is along the main valley of the glacier and the other in the direction of ENE is along the continental slope.

### 2.3. Surface feature in November 1975

Aerophotographs taken on November 29, 1975 cover the whole of the floating tongue of the Shirase Glacier, but for the comparison with the other years, the area shown in Fig. 4c is limited to the south of 69°45′S.

Fig. 4c shows calving of icebergs in the downstream of Instekleppane due to the development of both the longitudinal and transverse cracks reaching to the sea. The longitudinal size of icebergs is different in places. On the east side of the tongue, it is 5 to 7 km. This part corresponds to the east tributaries joined to the main stream of the Shirase Glacier at 5 to 10 km up from the Oku-hyôga Rock. The longitudinal size of icebergs in the central part of the glacier is 1.4 to 1.9 km, which is deduced also from the existence of many hidden cracks as shown by dashed lines in the figure. In the western

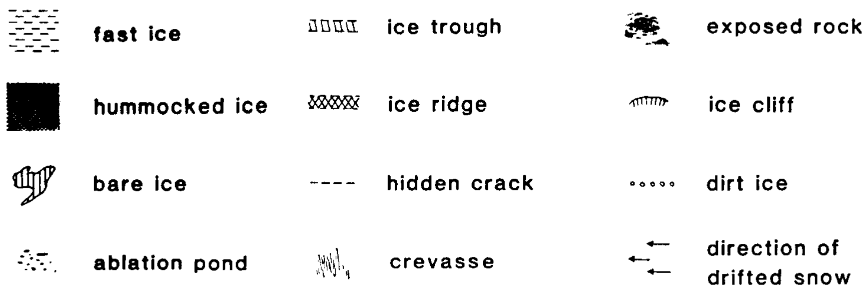


*Fig. 3. The legend of the surface features of the Shirase Glacier used in Figs. 4a, 4b, 4c and 4d.*

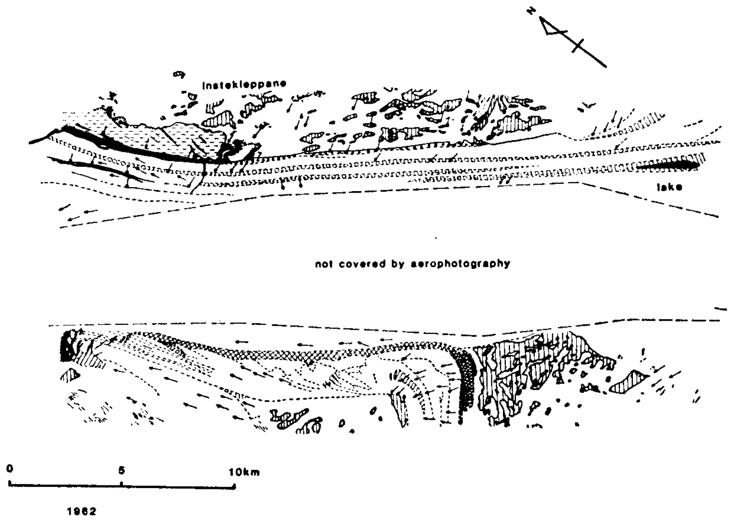


*Fig. 4a. The surface feature of the Shirase Glacier on January 21, 1962.*

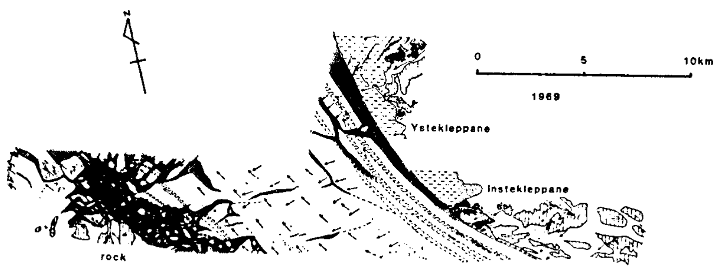


*Fig. 4b. The surface feature of the Shirase Glacier on January 21, 1969.*

part of the glacier, many icebergs with various size which were calved from the west tributary are existing in the hummocked sea ice.

The lake observed in January 1962 (in Fig. 4a) is again shown in Fig. 4c nearly at the same position after about 14 years. This suggests that the lake is not an ablation lake on the surface of moving glacier but is existing as a fissure within the ice resulting from

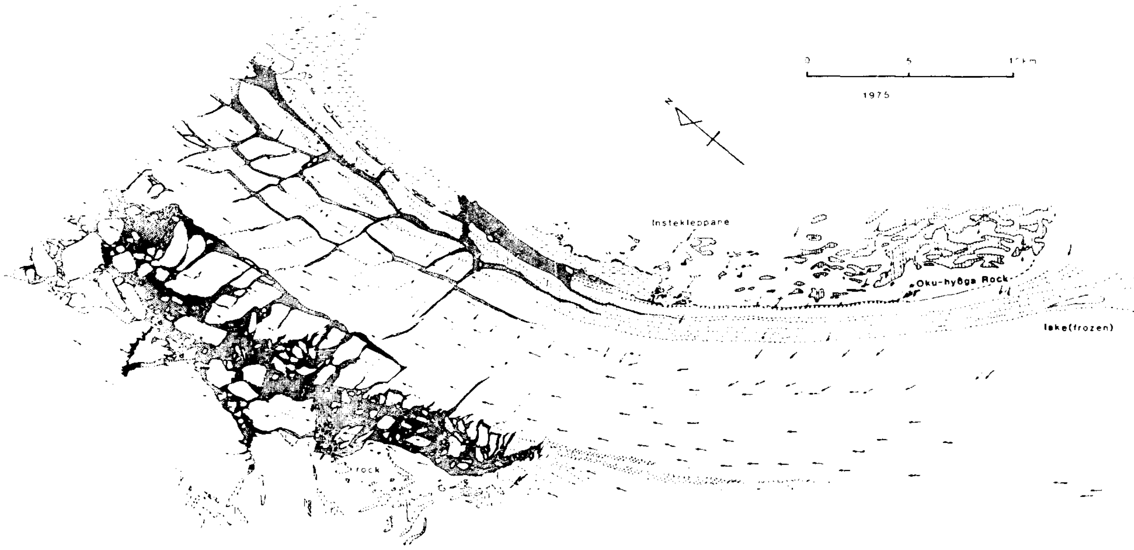


*Fig. 4c. The surface feature of the Shirase Glacier on November 29, 1975.*

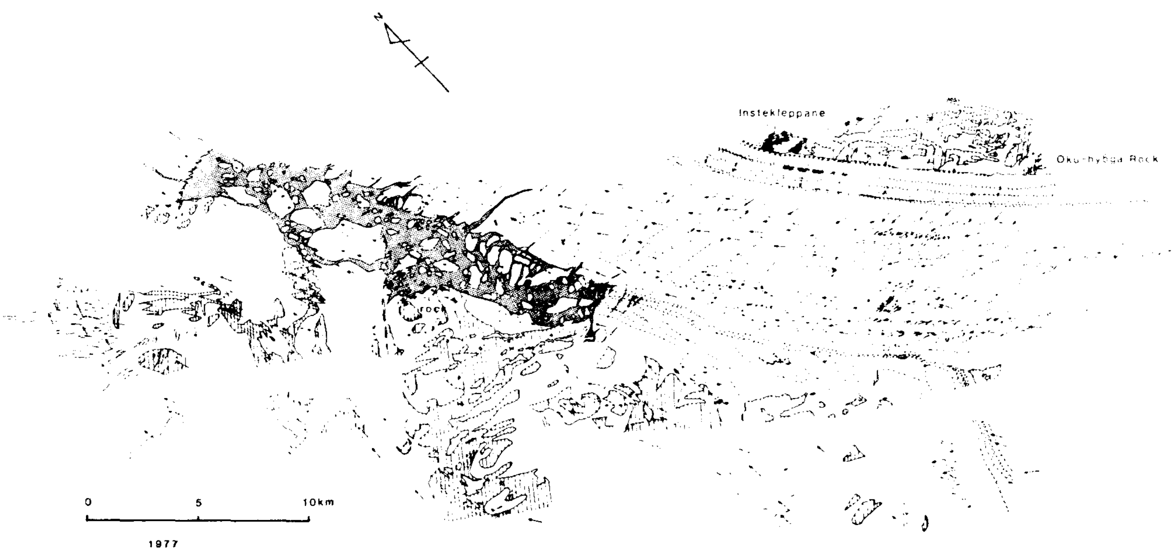


*Fig. 4d. The surface feature of the Shirase Glacier on January 19, 1977.*

the mechanical interaction between the subglacial topography and the movement of the glacier. Two katabatic wind systems shown in Figs. 4a and 4b are also shown in Fig. 4c where the ENE wind system is not existing in the western part.

### 2.4. Surface feature in January 1977

Fig. 4d shows the surface feature in January 19, 1977. The previous aerophotographs of 1962 and 1969 were taken also in January, but the existence of numerous ablation ponds is shown only in the photos taken in 1977. The mean air temperature at Syowa Station in December 1976 - January 1977 was 0.5°C, whereas the temperatures in the same duration of 1961–1962 and 1968–1969 summer were −2.4°C and −0.9°C, respectively. There was no distinctive difference in the global solar radiation at Syowa Station in these three summer seasons, so the development of ablation ponds may be due to the higher air temperature in the 1976–1977 summer.

A tributary coming from the west of the Shirase Glacier joins the main stream at an angle of about 60°. The distinctive calving front of the west tributary is opposite Instekleppane and many icebergs with different sizes are scattered in the hummocked sea ice. The different ice calving scheme between the west tributary and the main stream of the Shirase Glacier suggests that the ice discharge of the Shirase Glacier is attributed to these two subdivisional outlets, that is, the west tributary and the main stream.

The directions of two katabatic wind systems in 1977 shown in Fig. 4d scarcely differ from those in 1962, 1969 and 1975. This means that the direction of katabatic wind changes little from year to year.

## 3. Flow Velocity in 1969–1975 and 1975–1977

In 1960, FUJIWARA and YOSHIDA (1972) made the first measurement of the flow velocity of the Shirase Glacier. They set two stakes on the icebergs near Ystekleppane in May and resurveyed in September after 147 days, giving the displacement of 837 m and 855 m, or the mean annual velocity of 1.8 and 2.0 km·a$^{-1}$, respectively.

NAKAWO *et al.* (1978) obtained the mean annual velocity of 2.4 to 2.7 km·a$^{-1}$ near Ystekleppane in analyzing the displacement of 5 icebergs which were photographed

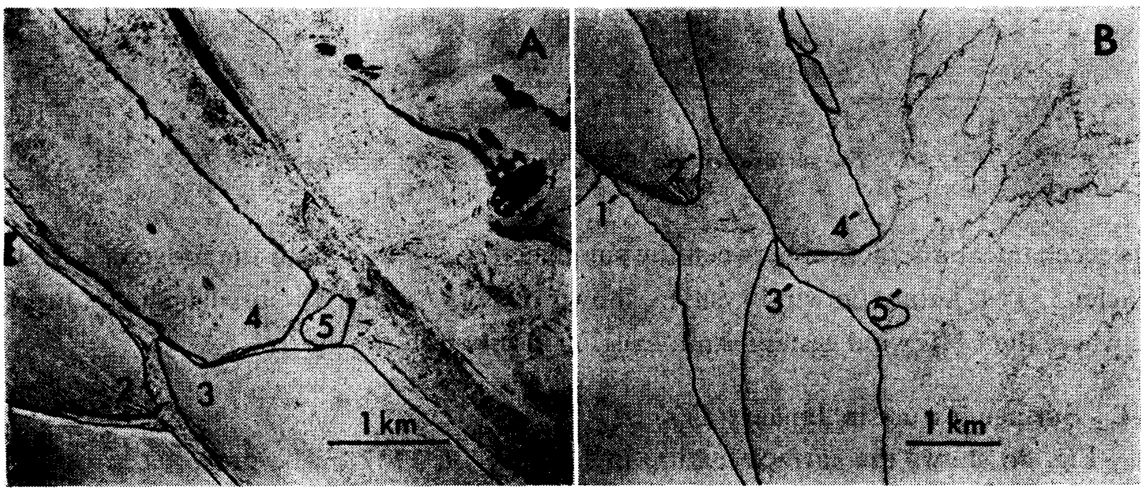


*Fig. 5. Time lapse photo pairs of five icebergs near Ystekleppane in January 1969 (A) and November 1975 (B) (after NAKAWO et al., 1978).*

on January 21, 1969 and November 29, 1975 (Fig. 5). This kind of velocity estimation had been reported by KUSUNOKI and ONO (1964) on glaciers along the Prince Olav Coast.

The method of determining the mean annual velocity of glacier flow and ice sheet flow in this paper is more or less the same as that by the previous authors. In measuring the displacement of conspicuous features which appeared in aerophotographs taken on January 21, 1969, November 29, 1975 and January 19, 1977 at many localities, values of annual flow velocity of the Shirase Glacier and the sheet flow in the west of the glacier are obtained. The results will be described below.

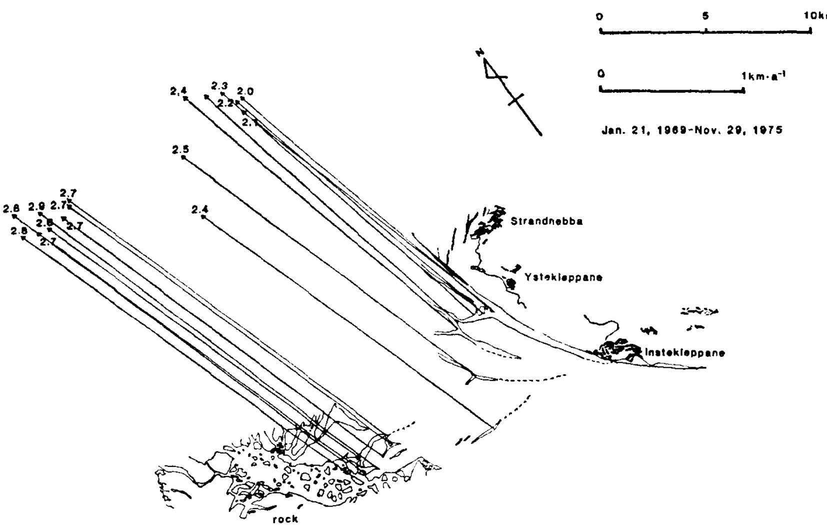


*Fig. 6a. The displacement arrows of several points of the Shirase Glacier and icebergs from January 21, 1969 to November 29, 1975.*

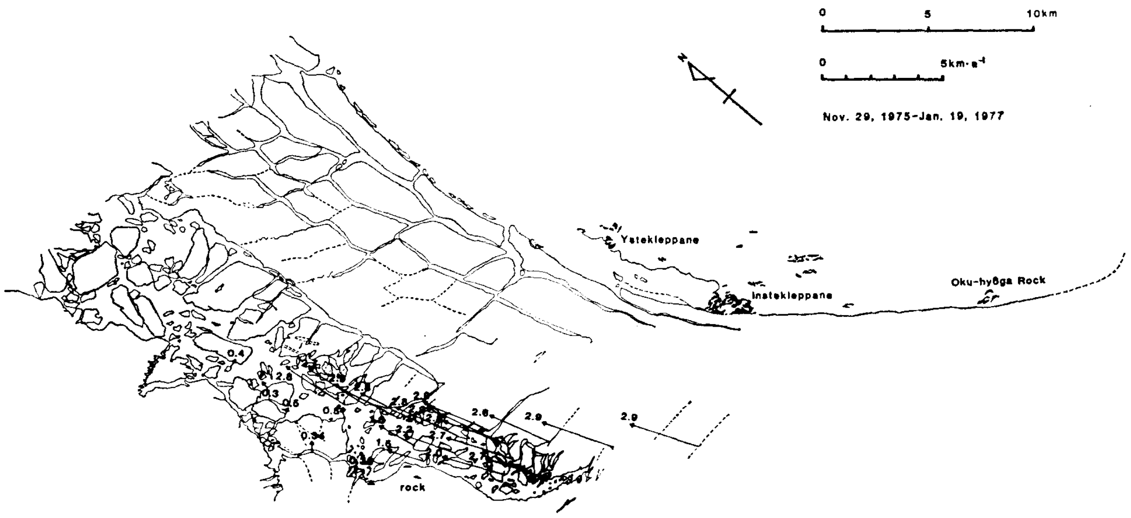


*Fig. 6b. The displacement arrows of several points of the Shirase Glacier and icebergs from November 29, 1975 to January 19, 1977.*

### 3.1. Mean annual velocity in January 1969-November 1975

Fig. 6a shows the displacement vectors at several points of the Shirase Glacier and the icebergs during 6 years and 10 months, where arrows stand for the position in January 1969. Arrows indicate that the speed of the Shirase Glacier increased from the east side (2.0–2.4 $km \cdot a^{-1}$) to the west side (2.6–2.9 $km \cdot a^{-1}$), being 2.5 $km \cdot a^{-1}$ on an average.

### 3.2. Mean annual velocity in November 1975-January 1977

Since the overlapping of aerophotographs on the east side of the Shirase Glacier taken in November 1975 and January 1977 is insufficient, the flow scheme of the glacier and icebergs is analyzed mainly on the west side (Fig. 6b).

The mean annual velocity during this period is about 2.9 $km \cdot a^{-1}$ deduced from the movement of transverse cracks on the west side of the main stream; about 2.7 $km \cdot a^{-1}$ was obtained at the west fringe which is a part of the west tributary of the Shirase Glacier. The mean annual velocity of the west side of the main stream flow of the Shirase Glacier during this period seems to have increased slightly compared with that in the previous 6 years and 10 months. As for the mean annual velocity of the sheet flow in the west of the Shirase Glacier, 0.34 $km \cdot a^{-1}$ and 0.38 $km \cdot a^{-1}$ were obtained at two points of the calving front in the west of an unnamed exposed rock.

## 4. Thickness of Icebergs Near Calving Front

Thickness $d$ of floating icebergs or glacier tongue is calculated by the following equation:

$$d = h \cdot \rho_w / (\rho_w - \rho_i)$$

where $h$ is the height above the sea level, $\rho_w$ (1.03 $g/cm^3$) the density of sea water, and $\rho_i$ (0.90 $g/cm^3$) the density of glacier ice. The height of iceberg $h$ is determined from a stereo-pair as shown in Fig. 7. As there is no height control point in this stereo-pair, the surface of flat sea ice was taken as the reference level of 0 m, and the height of icebergs was determined with a Wild B8S Aviograph Stereoplotter. Measured heights are given in Fig. 8.

The height of icebergs from the main stream (area A in the figure) of the Shirase Glacier ranges from 65 m to 70 m, except a value of 40 m at the fringe of an iceberg. These heights correspond to the thickness of 515 to 554 m. On the other hand, the height of icebergs from the west tributary (area B) is approximately 55 m to 65 m, giving the thickness of 436 m to 515 m. The height of icebergs in area C, originated from the sheet flow in the west of the Shirase Glacier, was 25 m to 30 m, giving the thickness of 198 m to 238 m.

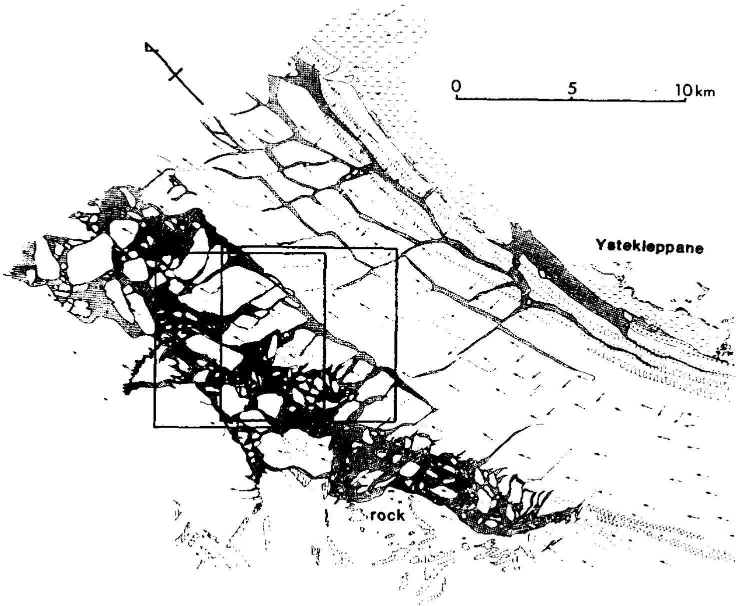


*Fig. 7. Areas of a stereo-pair for aerophotogrammetric height determination of icebergs.*

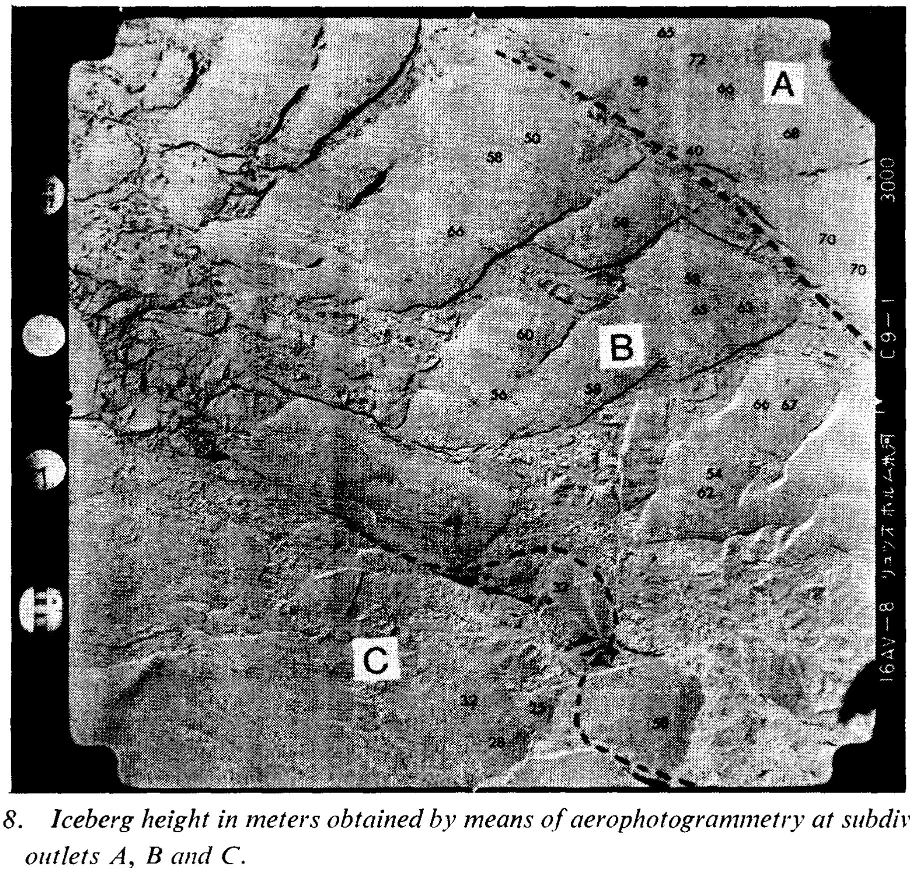


*Fig. 8. Iceberg height in meters obtained by means of aerophotogrammetry at subdivisional outlets A, B and C.*

Ground surveys of the height at the terminus of the Shirase Glacier gave 30 m to 70 m by NAGATA and YOSHIDA (1962) and 48 m by AGETA (1971). By analyzing the shadows of icebergs in aerophotographs, NAKAWO *et al.* (1978) gave the height of 40 m to 64 m. Their values are lower than the present values. This difference may be attributed to the facts that the ground surveys were made at the much ablated terminus of the floating tongue and the aerophotographic analysis by NAKAWO *et al.* (1978) was based on the length of shadows thrown from the lower fringe of iceberg which has a higher elevation in the central part.

## 5. Ice Discharge from the Shirase Drainage Basin

As described in Sections 3 and 4, the flow velocity and the thickness of icebergs or the floating glacier tongue are different in places. Taking these differences into account, the outlet of the Shirase drainage basin can be divided into three; (A) the main stream of the Shirase Glacier, (B) the west tributary of the Shirase Glacier and (C) the

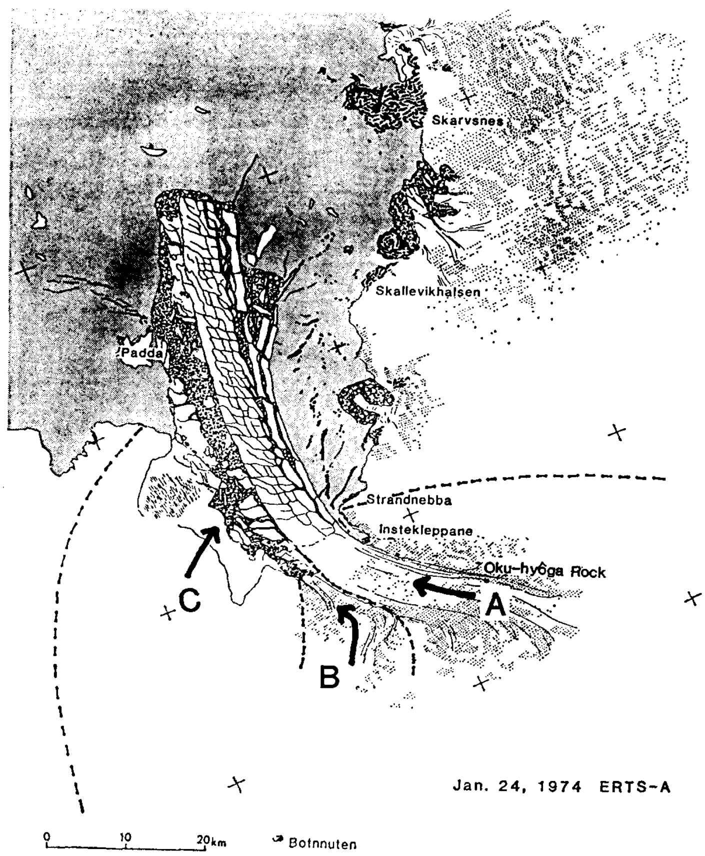


*Fig. 9. Ice discharge from three subdivisional outlets; A: main stream of the Shirase Glacier, B: west tributary of the Shirase Glacier and C: sheet flow in the west of the Shirase Glacier.*

*Table 2. Discharge of ice from subdivisional outlets of the Shirase drainage basin with their basic components. Assumed values are in parentheses.*

| Drainage subdivision | Height of iceberg (m) | Ice thickness (m) | Flow width (m) | Flow velocity ($m \cdot a^{-1}$) | Discharge ($\times 10^9\ t \cdot a^{-1}$) |
|---|---|---|---|---|---|
| A | 65–70 | 515–554 | 8650 | 2500 | 10.0–10.8 |
| B | 55–65 | 436–515 | 1900 | 2700 | 2.0– 2.4 |
| C | (25–30) | (198–238) | (20000) | (360) | (1.4–1.5) |
| | | | Total discharge | | 13.4–14.7 |

sheet flow outlet in the west of the Shirase Glacier as shown in Fig. 9.

The amount of ice discharge at three subdivisional outlets of the Shirase drainage basin is calculated by a simple multiplication of the velocity, the width, the thickness and the presumed density of ice 0.90 g/cm$^3$, assuming that the cross section of the outlet is quadrangle. Table 2 shows the amounts of ice discharge with their basic data of height of icebergs, ice thickness, flow width and flow velocity as described in the previous sections. As for the subdrainage C, the present study assumes that the drainage C ends in a 20 km long coast line, so the figures are given in parentheses. As shown in Table 2, the annual total discharge of ice from the Shirase drainage basin is estimated to lie between 13.4 and $14.7 \times 10^9\ t \cdot a^{-1}$, about 90% of it is fed by the Shirase Glacier (A and B in Table 2).

## 6. Concluding Remarks

Analyses of aerophotographs taken in January 1962, January 1969, November 1975 and January 1977 identified distinctive surface structures, the existence of two katabatic wind systems and the amount of ice discharge calculated using both the analyzed flow velocity and ice thickness near the coastal fringe of the Shirase drainage basin.

Calculations of ice discharge are made for three subdivisional drainage systems which have different values of flow velocity and ice thickness. The estimated total discharge from the Shirase drainage basin, 13.4 to $14.7 \times 10^9\ t \cdot a^{-1}$, is larger than the previously estimated value of $7.4 \pm 1.9 \times 10^9\ t \cdot a^{-1}$ by NAKAWO *et al.* (1978). The difference may be ascribed to the underestimation of the glacier thickness by NAKAWO *et al* (1978); they calculated the thickness on the basis of the shadow length of the fringe of dome-shaped icebergs and the density of ice of 0.85 g/cm$^3$, but they used the density of 0.90 g/cm$^3$ in the calculation of ice discharge. Furthermore, in estimating the total discharge from the Shirase drainage basin, they disregarded the sheet flow ice discharge from the 20 km long coast in the west of the Shirase Glacier.

The mass budget of the ice sheet in the Shirase drainage basin is estimated to be

$-0.7$ to $-2.0\times10^9$ t·a$^{-1}$ during the last several years, subtracting the ice discharge from the income mass of $12.7\times10^9$ t·a$^{-1}$ which is the mean of the maximum and the minimum surface mass budget of 1969–1975 given by YAMADA and WATANABE (1978). It can be said that the ice in the Shirase drainage basin was decreasing at a rate of 0.7 to $2.0\times10^9$ t·a$^{-1}$ during the last several years. The present estimation of the mass budget is much different from the value of $+5.3\times10^9$ t·a$^{-1}$ given by SHIMIZU *et al.* (1978b) who used the outgoing mass of $7.4\times10^9$ t·a$^{-1}$, which was estimated by NAKAWO *et al.* (1978) and also disregarded the ice discharge from the 20 km long coast in the west of the Shirase Glacier.

The present study shows the usefulness of aerophotographic analyses to estimate the velocity of flow, the thickness and the amount of ice discharge in an outlet area as well as for the collection of information of surface features in such an inaccessible area as is the case with the present study. Further studies are required in the sheet flow area in the west of the Shirase Glacier for more reliable estimation of total ice discharge from the Shirase drainage basin. Aerophotographic reconnaissance flights over the ice fringe area with an appropriate time interval are badly needed for monitoring the fluctuation of flow velocity and ice discharge.


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